THE DYNAMICS OF WATER DROPLETS IN A COUNTERFLOW FIELD AND ITS EFFECT ON FLAME EXTINCTION

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Introduction

Efficient suppression of flames by condensed-phase agents (e.g. dry powder, water, etc.) requires a basic understanding of the rate-controlling physical, thermal and chemical processes. A steady, laminar, non-premixed flame, established within the mixing layer of a counterflow of methane and air, is used here to numerically determine the rate controlling processes associated with flame extinction by fine water droplets. Although experiments are planned to validate the model, only the numerical results with water droplets introduced with the air stream are reported here.

Numerical Calculations

In implementing particle effects to the existing quasi one-dimensional flame code [1], Eulerian-Eulerian formulation can, in theory, be adopted to describe the gas-phase and particle-phase interactions [2]. However, for large particles, the "push back" effect (i.e. if the particles are large enough to penetrate through the stagnation plane, then the on coming methane stream can reverse their direction of motion) gives rise to a singularity in the particle number density equation [3]. To overcome such singular points, it is found convenient to implement a hybrid Eulerian-Lagrangian formulation for gas-particle phases. The resulting Lagrangian equations for mass, momentum, energy and particle flux fraction (normalized by that at the air nozzle exit) are integrated in time to determine the particle location and source terms contributing to the gas-phase conservation equations. The two sets of equations are then iterated until a predetermined convergence criterion is reached. Using this modified counterflow nonpremixed flame code, the water particle dynamics in a reacting counterflow field with and without mass evaporation are performed and are presented here.

Results and Discussion

When a single droplet is introduced with the air stream to a counterflow flame, the temperature and the velocity of the droplet can be different from that of the local gas-phase. The resulting thermal and momentum lag will control the heat transfer rate to the droplet and the subsequent cooling of the gas, leading to different extinction characteristics at different particle loading and size.

If interactions between particles and the gas-phase is neglected, then the integration of Lagrangian equations controlling the dynamics of a *single* water particle gives trajectories as shown in Fig. 1, for particle sizes ranging from 10-70 μm. The 10 μm particle is seen to track the gas velocity closely, while the large particles show the "push back" effect, with several crossings of the stagnation plane. Depending on whether the mass evaporation and gas-particle interactions are included or not, the dynamics of the particles can differ slightly. The mass evaporation process itself is coupled to the droplet temperature and to that of the gas mixture. As the droplet enters the thermal mixing layer, there is a short transient period in which the droplet temperature approaches the boiling point, T_b [the actual droplet temperature, T_s ($< T_b$), can be estimated by using the Clausius-Clapeyron Equation]. During this transient time a thermal wave will propagate from the surface of the droplet to the interior of the droplet, with increasing surface temperature. The temperature of the droplet will eventually reach a steady value, T_s. The total duration for the droplet temperature to achieve this value T_s starting from the room temperature, T_∞, is strongly related to the original particle size, thermal diffusivity, and net heat flux from the gas-phase to the droplet. Accurate modeling of this transient droplet heating process plays a critical role in determining the mass evaporation, especially of large particles.

As far as fire suppression by the water mist system is concerned, the total mass released by the water droplets plays a major role. Clearly, this has an important thermal effect and a chemical effect (because of the modification of the gas temperature and the presence of water vapor which can modify the finite-rate chemistry). Instead of a single water droplet, if a group of noninteracting monodisperse droplets are introduced with the air stream, then the integration of the "particle equation" indicate that the number density of the droplets changes along the axis of symmetry because of the flow straining effect. Assuming no particle interactions, the variation of particle flux fraction (particle number density normalized by that at the air stream exit) as a function of the axial location, for various monodisperse particles, is shown in Fig. 2. The total mass evaporation by such a group of noninteracting monodisperse droplets depends on the physical location, as shown in Fig. 1, and the number density variation due to the flow straining, as shown in Fig. 2. These two coupled effects on total mass evaporation, for water droplets of 10-70 μm are shown in Fig. 3. It is seen that 10 μm droplets vaporize completely before they reach the reaction front and cool the convective-diffusive zone on the air side. However, the water evaporated in this zone gets convected through the flame because the flame is located in the air-side of the stagnation plane. For droplets greater than 10 μm, evaporation occurs over a wider region; however, the total mass evaporation (area under the curve) can be a non-monotonic function of droplet size. Therefore, when the gas-particle interactions are included, the flame extinction condition is observed to be a non-monotonic function of particle size, but the exact role of thermal and chemical effects needs to be analyzed carefully.

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[3] Chen, N.-H., Rogg, B., and Bray, K.N.C., *Twenty-Fourth Symposium (Int.) on Combustion*, The Combustion Institute, p. 1513, 1992.

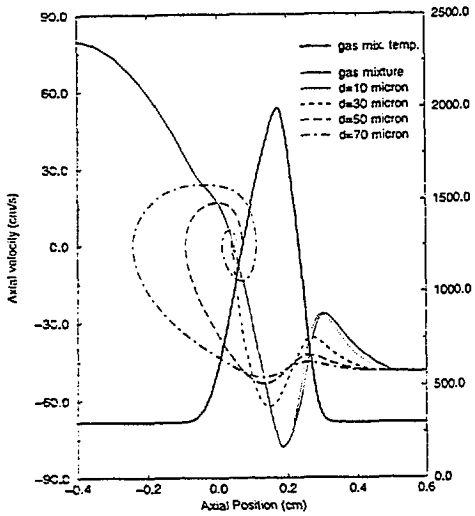

Figure 1: Particle velocities within the mixing layer, for selected particle sizes.

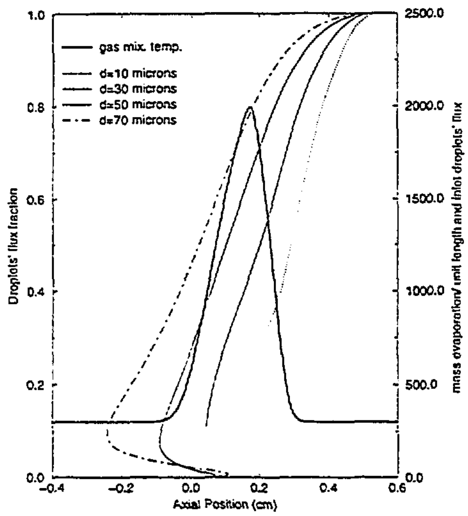

Figure 2: Change in particle flux fraction, for selected particle sizes.

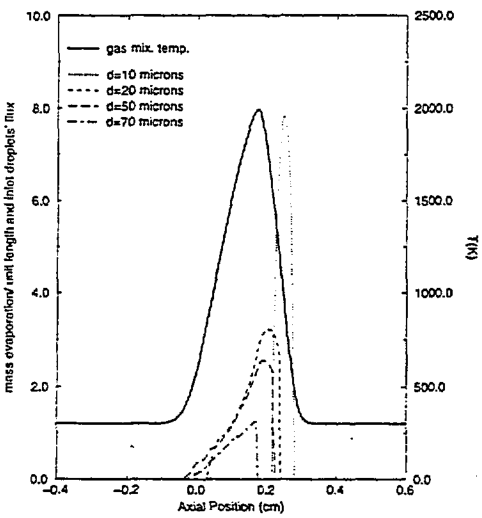

Figure 3: Net mass evaporation, for selected particle sizes.